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Towards a framework for assessment and management of cumulative human impacts on marine food webs

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Abstract:	Effective ecosystem-based management requires understanding ecosystem responses to multiple human threats, rather than focusing on single threats. To understand ecosystem responses holistically, it is necessary to know how threats affect different components within ecosystems and ultimately alter ecosystem functioning. We used a case study of the Mediterranean seagrass Posidonia oceanica food web and expert knowledge elicitation to apply the initial steps of a framework for assessment of cumulative human impacts on food webs. We produced a conceptual seagrass food web model, determined the main trophic relationships, identified the main threats to the food web components, and assessed the components' vulnerability to those threats. Some threats are expected to have high (e.g., coastal infrastructure) or low impacts (e.g., agricultural runoff) on all food web components whereas others (e.g., introduced carnivores) will have very different impacts on each component. Partitioning the ecosystem into its components enabled us to identify threats previously overlooked, and re-evaluate the importance of threats commonly perceived as major. By incorporating this understanding of system vulnerability, along with data on changes in the state of each threat (e.g., decreasing domestic pollution and increasing fishing) into a food web model, managers can better estimate and predict cumulative human impacts on ecosystems, and prioritize conservation actions.

Introduction

Ecosystems are impacted by multiple human threats simultaneously (Halpern et al. 2008a). Traditionally, however, resource management has considered human activities and their impacts in isolation, developing sector-by-sector policies and management strategies. This single-sector approach has proven largely ineffective, as it ignores or overlooks the many interactions among activities and their cumulative effects (Halpern et al. 2008b). Recently, management focus has shifted to more integrated approaches, such as ecosystem-based management (EBM), which consider the complexity of human pressures upon ecosystems, with the aim of managing the sustainability of ecosystems and their services to humans (Levin et al. 2009).

Management decisions ideally should be guided by an understanding of how ecological components or specific ecosystem services respond to multiple threats in a given location. Management actions that focus on threat mitigation will have different and sometimes contradictory consequences for different ecosystem components and services based on how directly or indirectly those ecosystem attributes are affected by the threat (see Halpern et al. 2008b), and how each service is linked to specific ecosystem components. Thus, for effective and efficient EBM implementation, it is important to understand not only how anthropogenic threats diffuse across space, but also how those threats affect different components within complex ecosystems, ultimately impacting their interactions, structure, and functioning. To date, cumulative impact assessments have focused on entire ecosystems, essentially averaging the effect across all species (e.g., Halpern et al. 2008a; Ban et al. 2010) or on single species or taxa (e.g., Maxwell et al. 2013).

Framework for assessment of cumulative human impacts on marine ecosystems: the importance of food webs

We propose a framework that accounts for food web interactions (Fig. 1) to better understand how human threats affect different ecosystem components, and consequently ecosystem functioning. The first step of the framework is to produce a static food web model that encompasses major trophic groups. Trade-offs between complexity and data availability should be considered. Then, definition of major trophic interactions and organic matter flows in the system is required (step 2), while major threats to each ecosystem component should also be identified (step 3). To address the challenge of tracking impacts on different food web components requires teasing apart the direct and indirect responses of ecosystem components to each threat type (step 4), in turn producing a more comprehensive understanding of why and how ecosystems respond to the cumulative impact of human activities (step 7). By generating a food web model, that includes trophic dynamics (step 5) as well as predictions on how human impacts affect ecosystem components (step 6), one should be able to provide more accurate assessments of direct effects on ecosystems as well as indirect effects, such as trophic cascades (step 7). Inserting stressors into a dynamic food web model will allow a more sound estimation of cumulative impacts on ecosystems, which will provide decision-makers better guidance on management action prioritization for the maintenance of ecosystem function and services (step 8 and 9). This requires clear definition of the conservation objectives, which involves prioritization of desired outcomes related to specific ecosystem services.

Here, using a food web of the endemic Mediterranean seagrass *Posidonia oceanica* (Linnaeus) Delile ecosystem as a case study, we apply the initial steps of the proposed framework (steps 1 to 4 in Fig. 1). We provide a method for assessing the vulnerability of food web components to multiple threats using expert knowledge elicitation. In the absence of sufficient empirical data, expert knowledge has emerged as a key tool for rational decision-making in conservation (Burgman et al. 2011). Although the limitations of expert judgment are well recognized (see McBride et al. 2012), structured approaches to expert elicitation have proven to be a valuable tool in comparing human threats and their impacts on ecosystems or taxa when empirical data are scarce (e.g., Grech et al. 2012). We also suggest topics for future research to improve available knowledge where gaps are more pronounced. This approach should be relevant and applicable to other ecosystems at any location.

Methods

*C*ase study

In the Mediterranean Sea, meadows formed by the endemic seagrass *Posidonia oceanica* are widespread, spanning the coastal waters of 16 countries, but they have been subjected to rapid decline over the past 20 years (Giakoumi et al. 2013; Pergent et al. 2014). The *Posidonia oceanica* ecosystem has been studied more than any other in the Mediterranean with more than 2100 ISI publications (search on the Web of Science, using keyword “Posidonia” and refining search by “oceanica”, period covered: 1864 - 2014) and a substantial amount of grey literature (e.g., Boudouresque et al. 2012). Yet, empirical data are still missing regarding the vulnerability of various components of the seagrass food web to human threats. Therefore, an expert knowledge elicitation process was followed to obtain information.

Expert knowledge elicitation

A three-day workshop of 14 experts on the *P. oceanica* ecosystem and its threats took place in Corsica (France) in 2013, to acquire information that would allow us develop the initial steps of a framework for assessing cumulative human impacts on food webs. Before and during the workshop, expert knowledge was used to identify: 1. the main components of the seagrass food web, 2. the relationships among these components, 3. the main human threats to the food web, and 4. the vulnerability of the different components of *P. oceanica* food web to human threats (see Appendix S1 for description of elicitation process and Table S1.2 for available literature on threats' impacts on food web components).

Vulnerability assessment

To assess each components' vulnerability to human threats we used vulnerability measures based on those developed by Halpern et al. (2007) for ecosystems and Maxwell et al. (2013) for marine predators. The four adapted vulnerability measures were: scale of impact, frequency of impact, sensitivity to the impact, and recovery time (see Table S1.1). Scale and frequency of impact define level of exposure to the impact of a threat, sensitivity is the likelihood and magnitude of an impact on a food web component once the impact occurs, and recovery is the adaptive capacity of the food web component. Furthermore, a level of certainty (i.e. available evidence) was assessed for each food web component/threat interaction. We took the grand mean of these weighted averages of the four vulnerability measures to get a single score (from 0 to 4) that indicated how a given threat affects a particular food web component (see Appendix S1 for methods).

Results

Framework steps 1 and 2: Conceptual **P. oceanica** *food web model and trophic relations*

Based on the conceptual *P. oceanica* food web presented in Personnic et al. (2014) and key references describing trophic relationships in the *P. oceanica* ecosystem (Buia et al. 2000; Vizzini 2009), experts identified the principal components of the *P. oceanica* food web and identified major trophic interactions and organic matter flows in the system. The model includes functional compartments from producers to high level predators (Fig. 2 and Appendix S2 for detailed description).

Framework steps 3 and 4: Main threats and food web components' vulnerability

Experts identified 21 main human threats on the *P. oceanica* ecosystem, nine of which are sea-based while twelve are land-based (see Appendix S1 for threats' definitions). Some threats appeared to have high impacts on all food web components (Fig. 3, right hand side: coastal infrastructure, fish farms, etc.) whereas others had lower and very different impacts across functional compartments (e.g., introduced herbivores, climate change - sea level rise), and a last group had even lower effects on all components (e.g., introduced carnivores, agricultural runoff). All threats related to climate change, except for acidification, presented a high variation in their impacts across functional compartments, possibly reflecting limited available information.

The majority of food web components were most vulnerable to broad-scale irreversible coastal construction, such as ports, except for carnivores/omnivores and high-level predators. Carnivores/omnivores and high-level predators seemed to be more vulnerable to trawling and other fishing techniques, respectively, because these components are specifically targeted by such activities. Large fish farms, through increased sedimentation, nutrient load, and light restriction, were believed to be a second major threat for *P. oceanica* leaf canopy and associated epibiota, but with lower influence on higher trophic levels (Fig. 3). For most organisms, except for endofauna, trawling was amongst the top five threats. However, its rank differed among functional compartments. Industrial pollution was also amongst the top five threats for all food web components. Figure 3 also illustrates to which threats food web components were less vulnerable. However, such any preliminary conclusion of low vulnerability should be treated with caution as most of the low ranked threats (e.g., agricultural runoff and sea level rise) had the least certainty (see Appendix S3).

Gaps in knowledge

According to experts, *P. oceanica* leaves were the best documented food web component in terms of impacts from human threats followed by epibiota, *P. oceanica* roots and rhizomes, and macrograzers. The most poorly documented components were: endofauna, filter feeders, and high level predators. Overall, the impacts with the greatest level of certainty were related to the following threats: fish farms, irreversible coastal infrastructure, domestic pollution, and trawling. In contrast, information on impacts was almost non-existent for threats such as: agricultural runoff, thermal pollution, introduced carnivorous species, and sea level rise. Impacts from anchoring, fish farming (in adjacent area), and introduction of alien macrophytes could be more or less certain depending on whether they impacted lower or higher trophic levels. Unsurprisingly, the greatest variation in the scores attributed by experts to vulnerability measures was observed for the most poorly studied food web components and threats (see Fig. 2 & Table S1.2).

Discussion

Marine coastal ecosystems are threatened by multiple land- and sea-based threats acting in concert. Our results show that food web components differ in their vulnerability to human threats and are expected to react in different ways when exposed to them. These results generate a more precise estimate of how overall ecosystems will respond to the cumulative effect of anthropogenic threats. Consequently, detailed knowledge of the impacts of threats on ecosystems can identify threat mitigation actions with potential benefits to ecosystems and their ability to deliver desired ecosystem services. More importantly, this knowledge can identify where actions may produce unexpected results – even perverse outcomes from management - due to different responses of food web components (and the resulting food web interactions). Ecosystem-based management should be more effective when taking into account direct and indirect impacts of threats to different ecosystem components, rather than using ecosystem-wide or taxa-specific measure of impacts (Carey et al. 2014).

Partitioning the ecosystem into its components facilitated the identification of main threats to the ecosystem as a whole. For instance, when threats to *P. oceanica* ecosystem were initially identified based on Boudouresque et al. (2009), fishing practices (other than trawling) were not included as a major threat on *P. oceanica*, because the focus of that review was the plant itself and not the food web. However, when considering all ecosystem components, this threat was added as it directly threatens higher trophic levels of the food web. This has implications in prioritizing actions for the maintenance of ecosystem services. More specifically, the objective of maintaining seagrass meadows as a source for food provision may prioritize restrictions to fishing practices as an appropriate management action.

On the other hand, threats widely considered as major threats to seagrasses, such as agricultural runoff (Grech et al. 2012), appeared to be less important for *P. oceanica* (Fig. 2), which meadows are always absent from areas near large river discharges due to low salinity. In the absence of empirical data, experts attributed very low certainty to the impacts of this threat on all food web components. Such findings are particularly important from a management point of view, as further research is needed to assess the impacts of agricultural runoff on *P. oceanica* before investing conservation resources to mitigate this threat. The lack of impact assessment impairs the estimation of potential benefits from conservation actions mitigating this threat. At the same time, actions directed to address other threats where the impacts are more certain may be more efficient and reduce the risk of failure.

Interestingly, food web components showed a great variation in expected vulnerability to climate change related threats. This variation reflects the low level of certainty regarding the impacts of climate change to most functional compartments, and the need for further research on this field.

Overall, ecosystem components seem to be more vulnerable to local rather than global threats. This finding contrasts evidence from previous studies in the region (e.g., Micheli et al. 2013) and elsewhere (e.g., Ban et al. 2010). Certainty about the impacts of threats on whole ecosystems seems to decrease when experts focus on impacts to each ecosystem component separately. Just as segregating vulnerability into its components can provide a more accurate estimation of an ecosystems' vulnerability to threats (Halpern et al. 2007), identifying human impacts on each ecosystem component can help estimate the overall impacts of threats on ecosystems and provide insights on how these can be mitigated.

To assess the overall benefits of different sets of management actions on food webs, additional steps are needed (Fig. 1). A further step is the construction of a quantitative food web model using data on the biomass of functional compartments and fluxes between compartments. Interactions among organisms or functional compartments within food webs that are precipitated by the introduction or removal of multiple threats will determine the cumulative impacts on the food web. When a full model is available, relations between threats (synergistic, antagonistic or additive) can be quantified taking into account the structure of the food web and its dynamics. Then, the vulnerability values of food web components to human threats estimated here can be incorporated into the dynamic food web model for the parameterization of each food web component. Efficient prioritization of resources demands that we identify actions to address specific threats to, along with their corresponding costs and conservation benefits (Evans et al. 2011). Better estimation of cumulative impacts on the food web will allow better estimation of conservation benefits resulting from management actions.

The failure of management plans focusing on single activity mitigation to recognize that ecosystems suffer from cumulative consequences of multiple human activities has been compared to the failure of a medical treatment to recognize that a human illness may depend on a combination of factors e.g., diet, exercise, lack of adequate sanitation (Halpern et al. 2008b). Respectively, failing to assess impacts of threats on different food web components could be compared to failure to recognize the effect of an illness on critical human organs, such as the heart, liver, and kidneys. Assessments of cumulative human impacts on food webs, and then devising actions that mitigate those multiple threats, may assist in providing better “treatments” for stressed and unhealthy ecosystems.

Supporting Information

Methods on experts’ knowledge elicitation and vulnerability assessment, experts’ questionnaire, table with literature on empirical data at experts’ disposal, threats definition and relations to stressors (Appendix S1), as well as detailed description of the food-web (Appendix S2) and a radar chart presenting the uncertainty for each food web component/threat combination (Appendix S3) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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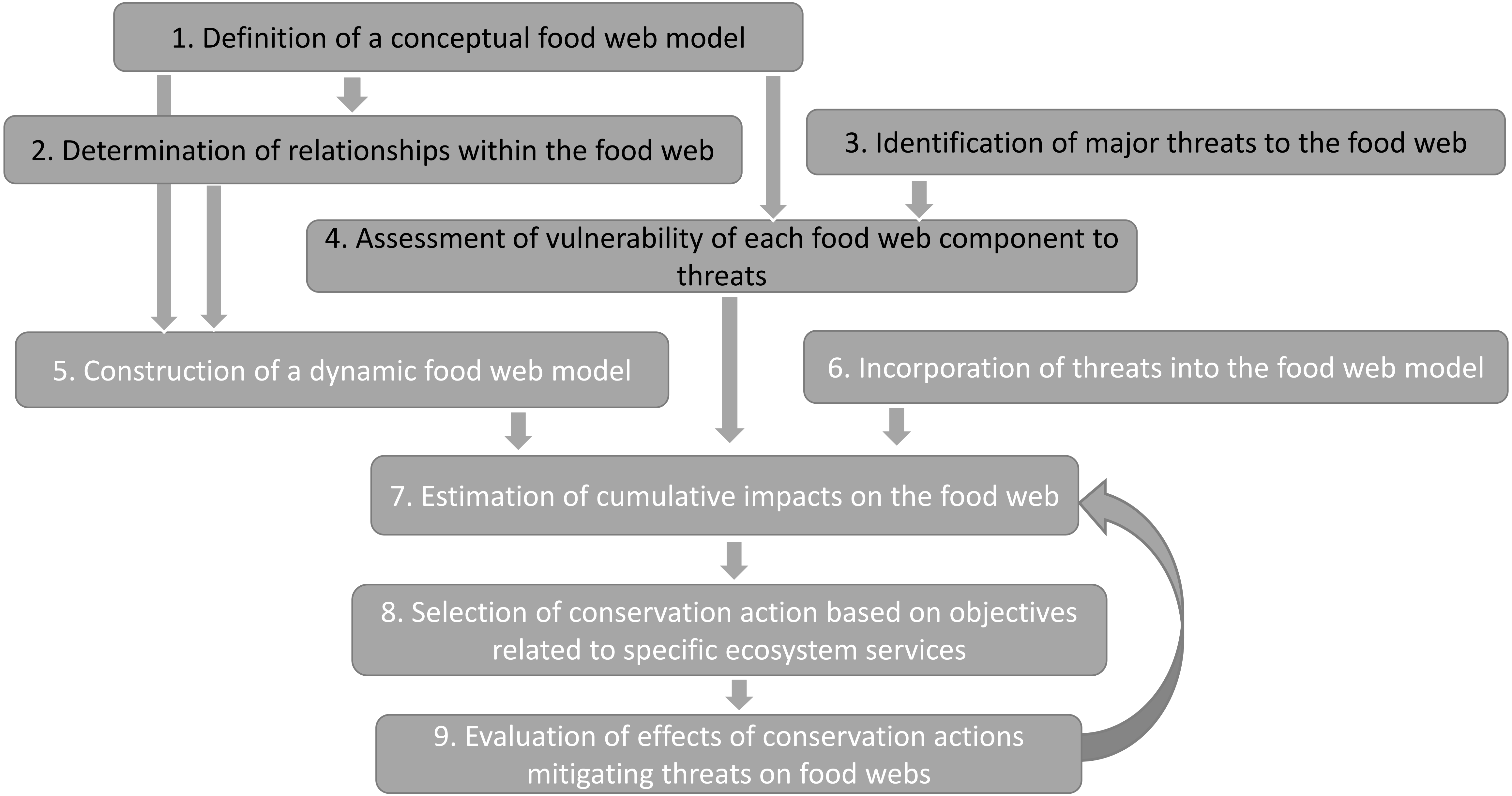
Figures Legends

Figure 1: Framework for the selection of management actions accounting for cumulative human impacts on food webs. Steps 1 to 4 (in black font) are presented through the seagrass case study, while further steps (5 to 9) are discussed.

Figure 2: Conceptual *Posidonia oceanica* food web model. Food web components appear in colored boxes. Green dashed line bounding box defines *P. oceanica* system. Grey dashed bounding boxes denote clusters of functional groups that share a common link to some other compartments. Black arrows represent transfer of energy among different compartments, while grey arrows indicate energy transfer among clusters of food web components. DOC: dissolved organic carbon, BAFHS: bacteria, archaea, fungi, and heterotrophic stramenopiles, SPOM: suspended particulate organic matter. Left top picture is courtesy of S. Ruitton.

Figure 3: Vulnerability of *Posidonia oceanica* food web components to human threats. Radar chart presenting the relative vulnerability of each food web component (illustrated as a different color) to each threat (each variable corresponding to a spoke).



1. Definition of a conceptual food web model

2. Determination of relationships within the food web

3. Identification of major threats to the food web

4. Assessment of vulnerability of each food web component to threats

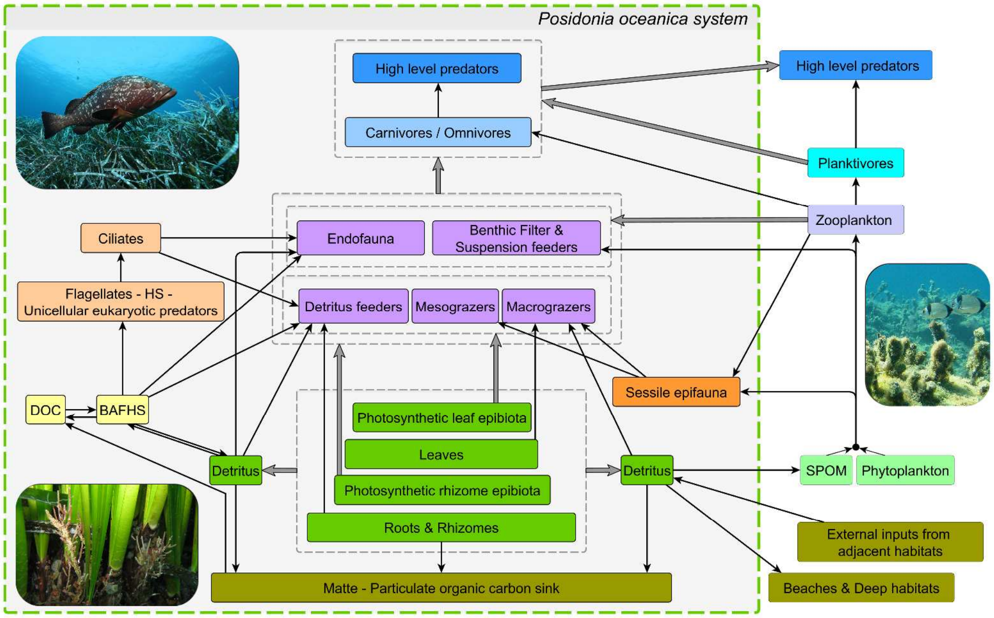
5. Construction of a dynamic food web model

6. Incorporation of threats into the food web model

7. Estimation of cumulative impacts on the food web

8. Selection of conservation action based on objectives related to specific ecosystem services

9. Evaluation of effects of conservation actions mitigating threats on food webs



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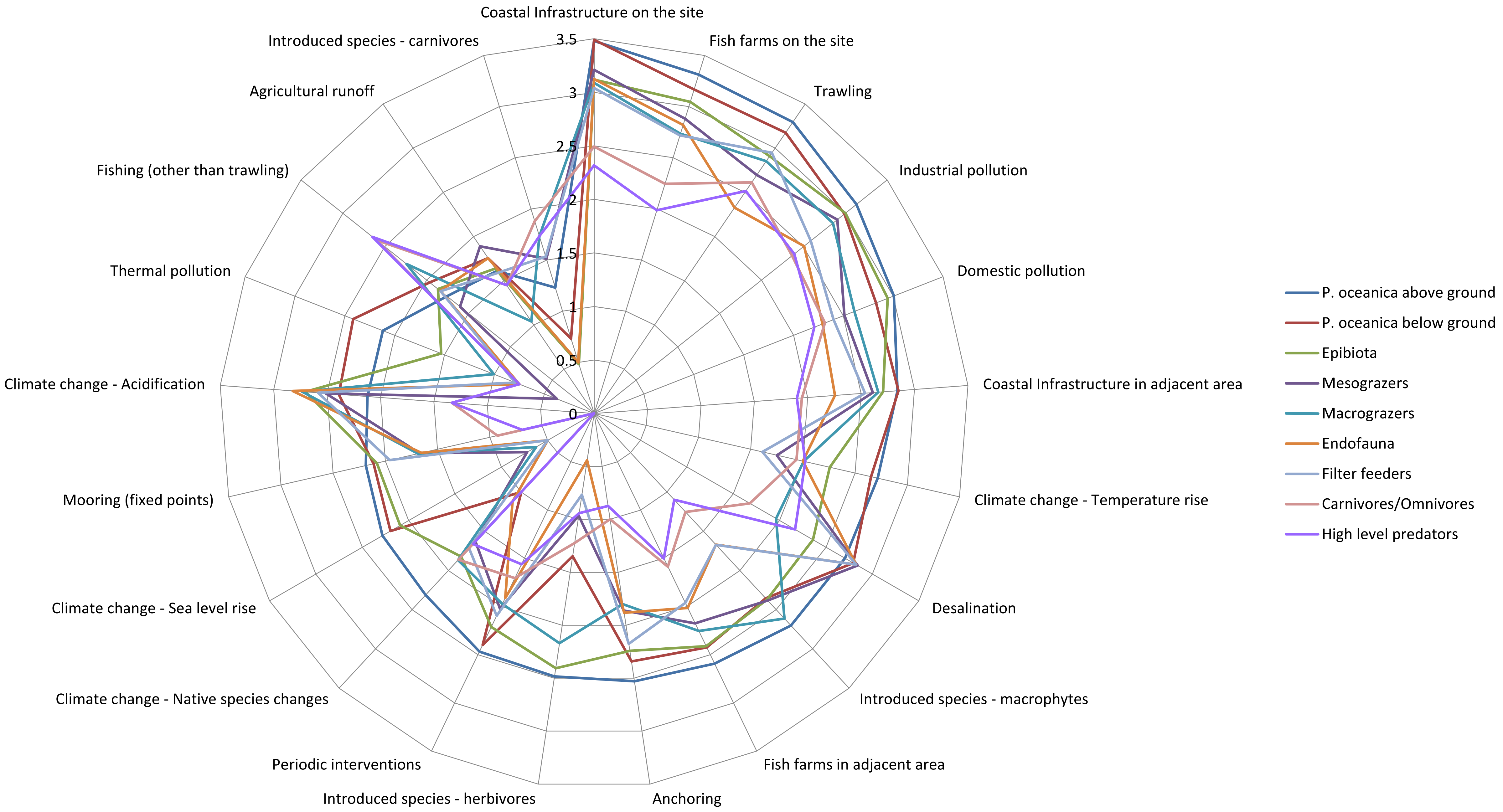
Coastal Infrastructure on the site
Fish farms on the site
Trawling
Industrial pollution
Domestic pollution
Coastal Infrastructure in adjacent area
Climate change - Temperature rise
Desalination
Introduced species - macrophytes
Fish farms in adjacent area
Anchoring
Introduced species - herbivores
Periodic interventions
Climate change - Native species changes
Climate change - Sea level rise
Mooring (fixed points)
Climate change - Acidification
Thermal pollution
Fishing (other than trawling)
Agricultural runoff
Introduced species - carnivores
3.5
3
2.5
2
1.5
1
0.5
0
P. oceanica above ground
P. oceanica below ground
Epibiota
Mesograzers
Macrograzers
Endofauna
Filter feeders
Carnivores/Omnivores
High level predators